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INVESTIGATION OF FLOW STRUCTURE DOWNSTREAM OF A CONE IN SUPERSONIC FLOW

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ABSTRACT: In the study reported here, schlieren photography, pressure sensors, and mechanical means of visualization were used to determine the pattern of pressure, motion, and flow regimes in the wake of a sharp cone in a Mach-3 flow. The nonuniform wake flow is found to exhibit an intensive central jet coming upstream to the cone's base and a toroidal eddy zone between the central jet and the jet boundary of the wake.

A great many papers have been published recently on the subject of the theoretical calculation of base pressure (for example, [1-3], etc.). On the basis of the scheme of Chapman and Korst [4,5], different additional assumptions are used in the calculation of the pressure in a wake zone behind flat and axisymmetric bodies exposed to a supersonic gas flow. An analysis of the correctness of different hypotheses and assumptions can be found in References 6, 7 and others, together with an evaluation of the accuracy of the resulting computational findings as compared to observations. Many particular aspects of the problem--mixing along the jet boundary of the wake zone behind the body, the effect upon the mixing of the boundary layer diverging from the trailing edge of the body, and the conditions of junction of the detached flow in the region of the throat of the body's trail--require further experimental investigation. Also of great importance is the investigation of the flow directly within the wake zone itself, particularly in problems related to the study of the oscillations of the base pressure and heat exchange on the base part. However, there are few experimental papers on this problem (see, for example, [8,9]), and they provide insufficient information on the pattern of the flow behind different bodies in a supersonic flow. /140*

In the present paper, we report the results of experimental studies of the flow structure behind a sharp cone with a vertex half-angle of 10° and a diameter of the base part of 150 mm, which was exposed to an airflow with the Mach number 3. In the observing section, the cone was fastened both on two sharpened lateral pylons and on a circular base holder whose length and diameter were chosen such as to have no influence on the magnitude of the mean base pressure. The base part of the cone and the base holder were drained. The fields of the total and static pressures were studied by means of sensors attached to a rod which was mounted in the base

*Numbers in margin indicate pagination in the original foreign text.

of the cone and could be moved in the direction of the principal flow. The total-pressure sensor was made of steel tubes with an inside diameter of 1 mm which were directed both with the direction of the principal flow and against it. The spacing between the /141 tubes was 5 mm. The static-pressure sensor consisted of a sharpened, drained plate. The measured pressures were recorded by GRM-2 grouped recording manometers. The pattern of the flow around the model was photographed through a Töpler apparatus.

Let us introduce the rectangular system of coordinates $x = X/r$, $y = Y/r$, $z = Z/r$ with the origin in the center of the base part of the cone, the x-axis directed as the on-coming flow, the y-axis parallel to the axis passing through the centers of the optical glasses of the working part, and the z-axis vertically upward; r is the radius of the cone.

The total and static pressures were measured in the xy-plane, perpendicular to the xz-plane, in which the lateral pylons are located to reduce the influence of the eddy trail emanating from them. The investigations showed that in the region of wake condensation jumps and of the trail throat, there are substantial gradients of the total and static pressures. In the immediate vicinity of the base part (with $x \leq 0.84$), the static pressure is constant and equal to $p = P/p_1 \approx 1.8$-2.0, where p_1 is the pressure of the oncoming flow. Starting at $x = 1.0$, the pressure on the base holder begins to increase and at $x = 4.4$ reaches the maximum value, equal to $p = 1.34$. Then the pressure decreases.

Fig. 1

In order to obtain additional information on the flow structure in the wake zone downstream of the cone, we used interchangeable thin steel plates of different shapes which were attached to the base in such a way as to be in the symmetry plane of the cone horizontally and vertically. In some of the experiments, the plates were covered with a visualizing compound consisting of a mixture of various kinds of oils, carbon black, and dyes; in other experiments, the plates were painted white and thin Kapron filaments were cemented to them. Furthermore, the filaments were cemented to thin steel crossbars which were attached to a steel main rod; the resulting "Christmas tree" was fastened in the center of the base part of the cone. The distribution of the visualizing compound and the position of the filaments during the experiment were photographed through the optical window of the observing section with still and movie cameras. The plates with visualizing compound were also photographed on a stand after the experiment. In this case, the plate exhibited a noticeable smearing of the visualizing compound away from its points of concentration by the closing condensation jump when the supersonic apparatus left the regime.

A photograph of the distribution of the visualizing compound on the surface of a plate mounted in the xy-plane is reproduced in Figure 1, where $ABCD$ is the outline of the plate and AD the fastening line. The plate indicates an axial symmetry of the flow; the enhanced boundary layer on the plate and the condensation jumps at the edges also affect the flow downstream of the body. However, the principal features of the pattern are preserved, while the distribution of the visualizing compound gives additional information on the flow in the wake zone. The photograph indicates the following regions of flow and lines:

1. A region of external nonviscous flow.

2. The jet boundary of the wake zone.

3. A distinct black line which apparently is the separation boundary of the gas mass flowing in region 1 and the gas mass entrained out of the wake zone.

4. The surface of the cone.

5. A region of toroidal eddy flow.

6. Divergence point of the flow detached from the rear edge of the body and joined to the plate surface in this region.

7. The region of flow in a central jet emanating from the divergence region 9; this region *7* corresponds to a region of compression.

The arrows in the photograph indicate the flow direction, which can be seen clearly from the direction of the filaments cemented to the half-plates. The photographs of plates with filaments also distinctly exhibit the toroidal eddy region (*5*) and the central jet region (*7*). In the presence of the plate in the base region, a mass of gas in the form of an intensive central jet enters the wake zone from the divergence region *6*. Upon reaching the base of the cone, the gas diverges in radial directions and is again ejected by the principal flow. At the same time, part of the gas carried downward along the flow through region *10* between lines *2* and *8*. As a result of this effect, the wake zone is open, in the terminology of Korst [4]; that is, it is continuously bled /142
of gas near the surface of the plate, the gas being replaced, of course, by an inflow of gas from the region of divergence. Region *6* receives the flow of gas detached from half the circumference of the cone's leading edge. With no plate present, owing to the symmetry of the flow in the base region, this bleeding of gas cannot take place. Although the central jet and the toroidal eddy will be present, the outflow line 8 must have a discontinuity in region *10* (Figure 1). The presence of the central jet is corroborated by the distribution of the visualizing compound over the bottom part of the cone in the absence of a plate. In the center,

there is a distinct light spot where the solution is washed out by the jet of air. The color becomes darker with decreasing distance

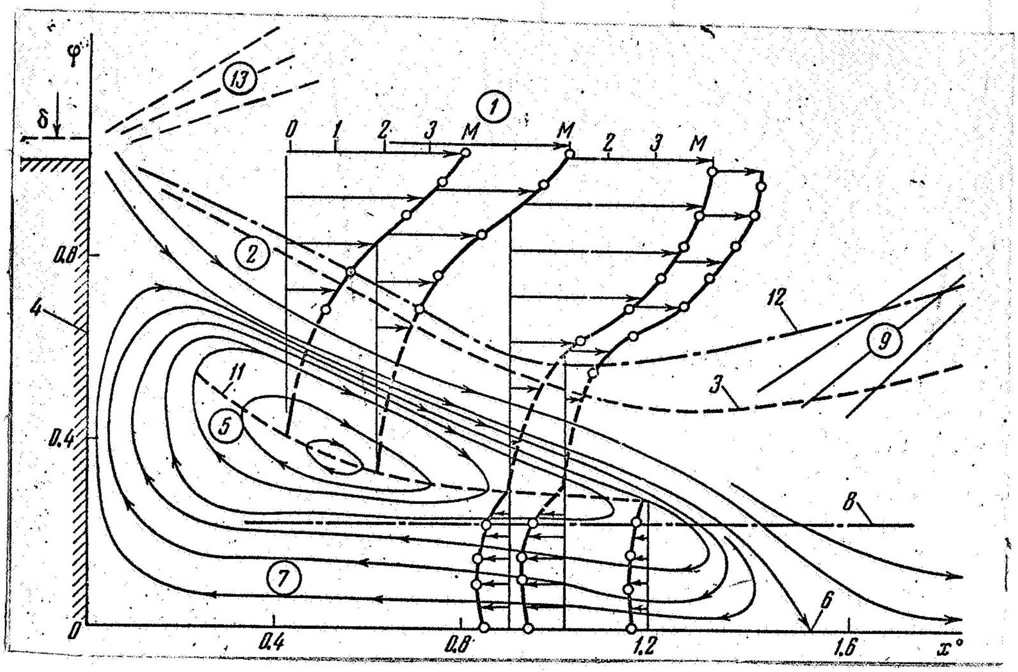

Fig. 2

to the periphery of the base. It must be noted that the light spot has an oval, rather circular, form, which is related to the influence of the viscous eddy trail emanating from the lateral pylons. The width of the central jet is also different on plates placed in the *xy*- and *xz*-planes. It is the smaller in the latter case. In the central jet, the total pressures and velocities are considerably greater than in the toroidal-eddy region. In the central jet, the Mach number, as computed from the total and static pressures, reaches the value 0.8.

Mach-number profiles are shown in Figure 2, which represents a diagram of the flow in the base region plotted on the basis of an analysis of all the data obtained. The nomenclature of the number labels is the same as in Figure 1. The line of the zero velocities, *11*, was plotted from data obtained from a photograph of the position of the filaments on the "Christmas tree" during the experiment. Line *12* is visible on the flow photographs taken through the Töpler apparatus and is the upper boundary of the wake zone. Line *12* goes higher than line *11*, and the trail throat as seen on the Töpler photographs is at greater distances from the base than is observed on the plate. Divergence point *6* is depicted in accordance with Figure 1; *13* is a Prandtl-Mayer flow. The unnumbered arrows indicate flow directions; δ is the thickness of the boundary layer on the cone.

Thus, the flow in the wake of a body in supersonic flow is nonuniform. It is characterized by the presence within the zone of an intensive central jet emanating from a compression region in the vicinity of the trail throat and proceeding to the base of the cone, and by the presence of a toroidal eddy flow situated between the central jet and the jet boundary of the wake zone.

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